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Title: Neutron Beta Decay as a Probe of Weak Interactions

Author(s): Saunders, Alexander

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Neutron Beta Decay as a Probe of Weak Interactions

Alexander Saunders

Los Alamos National Lab

Outline

- Why study weak interactions using neutron beta decay?
  - Because of the scientific reach
  - Because of the impact across nuclear and particle physics
- Neutron beta decay correlations
  - How and why you measure them
  - Some sample experiments from the field
- Neutron lifetime
  - The problem and its impact
  - Some recent and upcoming experiments

Neutron beta decay can have remarkable scientific reach

- Two choices for detecting a force carrier of mass M:
  - Direct detection, if enough energy available
  - Virtual effects, if not
- If energy is close to mass, then signal may be large and function of energy
- But if energy is much less than mass, then signal is *independent* of energy!
- So the smart thing to do is choose the experiment that gives the best precision

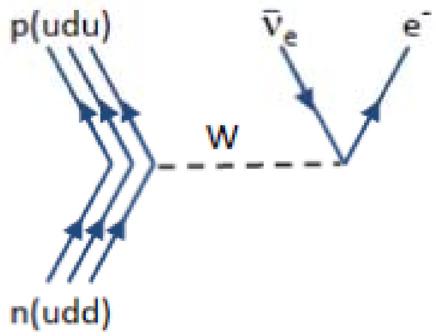
$$S \propto \frac{1}{M^2 - (p/c)^2}$$

$$S \propto \frac{1}{M^2}$$

Dubbers 2011

Neutron Decay Parameters

- Semi-leptonic decay
  - Lifetime 880 s
  - Endpoint energy 782 keV



$$n \rightarrow p + e^- + \bar{\nu}_e$$

- Just two free parameters in SM
  - CKM mixing matrix element
  - Ratio of weak coupling constants
  - Uncertainty comes from radiative corrections

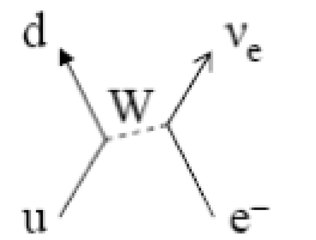
$$\tau_n = \frac{4908.7 \pm 1.9\ s}{|V_{ud}|^2 \left(1 + 3\lambda^2\right)}$$

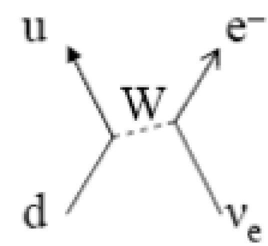
$$\lambda = g_A / g_V$$

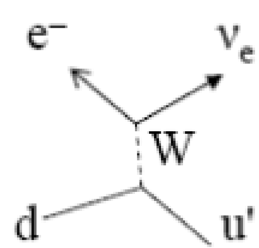
Neutron beta decay can inform many areas of physics

- Many reactions share the same Feynman diagram as neutron beta decay

Primordial element formation	$n + e^+ \rightarrow p + \nu'_e$	$\sigma_\nu \sim 1/\tau$
(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$	$\sigma_\nu \sim 1/\tau$
	$n \rightarrow p + e^- + \nu'_e$	τ
Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$	
	$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.	$\sim (g_A/g_V)^5$
Neutron star formation	$p + e^- \rightarrow n + \nu_e$	
Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$	
Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$	
Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.	
W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.	

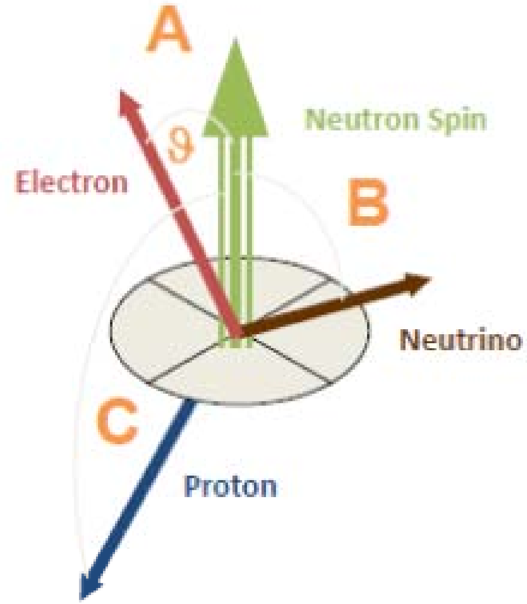






Decay Correlations

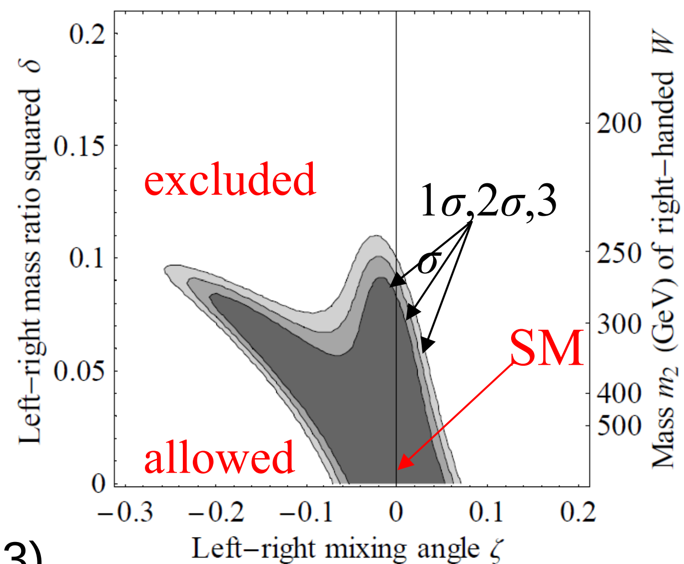
- A: electron asymmetry $\vec{\sigma}_n \cdot \vec{p}_e$
  - Perkeo II, Perkeo III, UCNA
- B: neutrino asymmetry $\vec{\sigma}_n \cdot \vec{p}_\nu$
  - Perkeo II
- C: proton asymmetry $\vec{\sigma}_n \cdot \vec{p}_p$
  - Perkeo II
- D: triple correlation $\vec{\sigma}_n \cdot \left(\vec{p}_e \times \vec{p}_\nu\right)$
  - TRINE, emiT
- a: electron-neutrino correlation $\vec{p}_e \cdot \vec{p}_\nu$
  - aSpect, aCORN, Nab



Plus Fierz interference *b*, helicity correlations, etc.

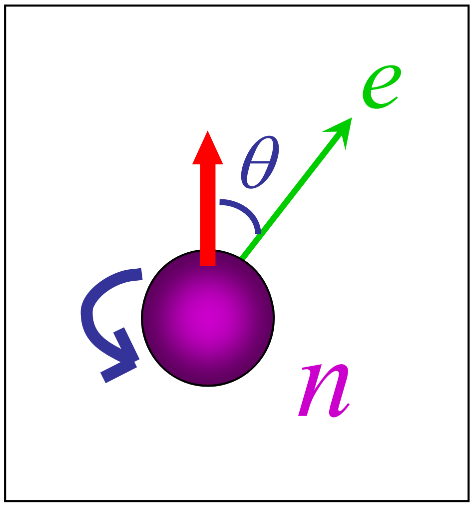
Search for new physics

- A single parameter yields λ, multiple measurements yield V_{ud} and beyond
- CKM unitarity $$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
  - Do neutrons and superallowed beta decays agree?
- Search for right-handed currents (250 GeV limit from n decay)
- Scalar and tensor couplings from *B* and *b*
  - Cirigliano 2012

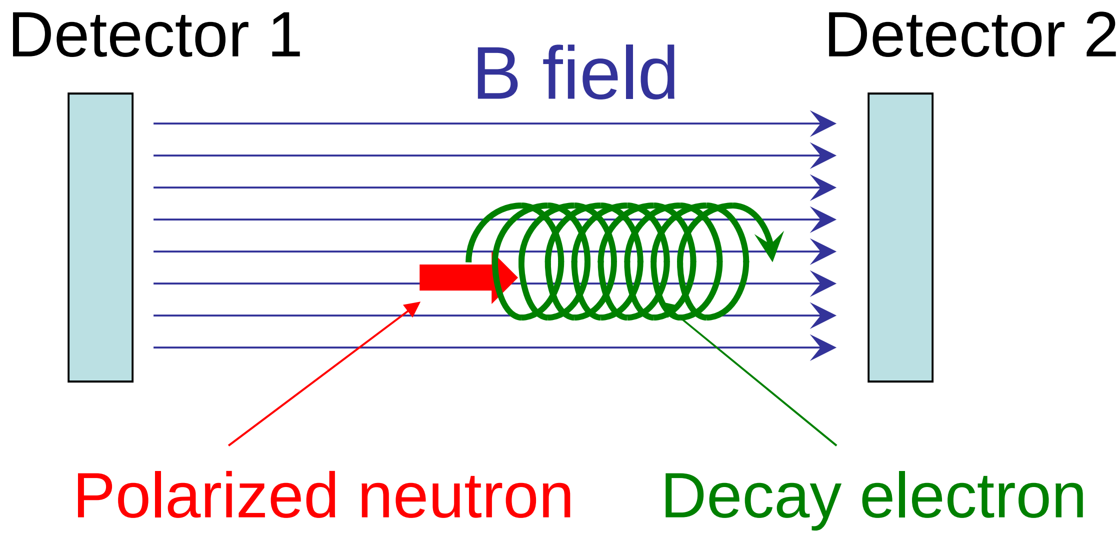


Holeczek *et al*., arxiv 1303.5295 (2013)

Principle of the *A*-coefficient Measurement (and *B* and *C* as well)



$$dW = [1 + \beta P A \cos\theta]\, d\Gamma(E)$$



$$A_{\exp}(E) = \frac{N_1(E) - N_2(E)}{N_1(E) + N_2(E)} \approx \langle P \rangle A \beta \langle \cos\theta \rangle$$

(End point energy = 782 keV)

Potential Sources of Systematics

- Neutron polarization determination
- Background
  - Due to neutrons that do not decay
- Detector-related effects
  - Electron backscattering and spectroscopy
  - Edge effect (fiducial volume selection)
  - Detector response, calibration
- Statistics
  - Large decay volume, high density

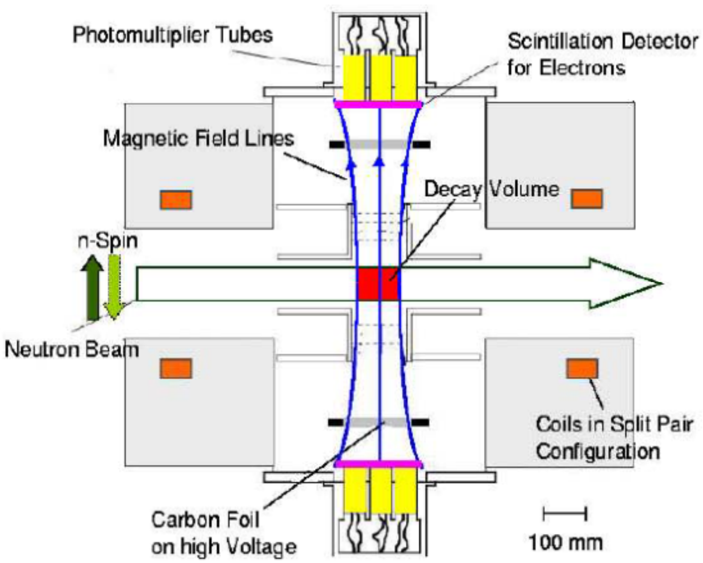
Perkeo II Experiment Measured ABC

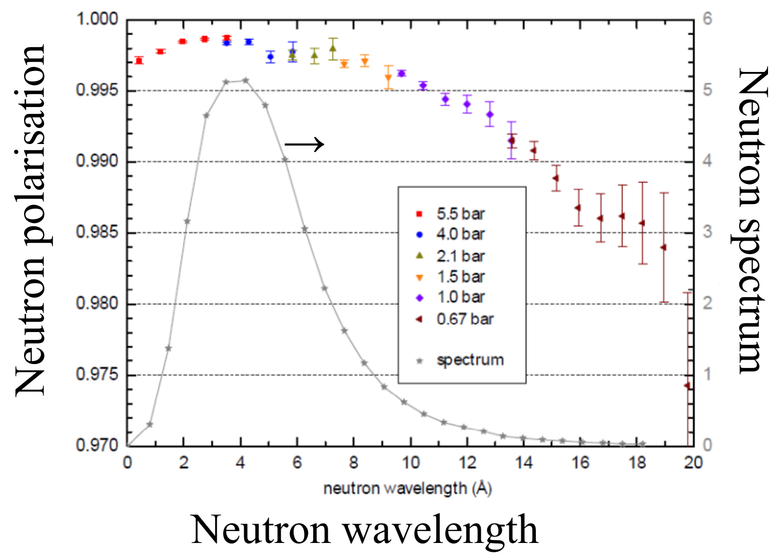
PERKEO II:

β-Asymmetrie $\quad A = -\,0.1200 \pm 0.0006$, PRL, in print (2013)

p-Asymmetrie $\quad B = +\,0.983 \pm 0.005$, PRL **99**, 191803 (2007)

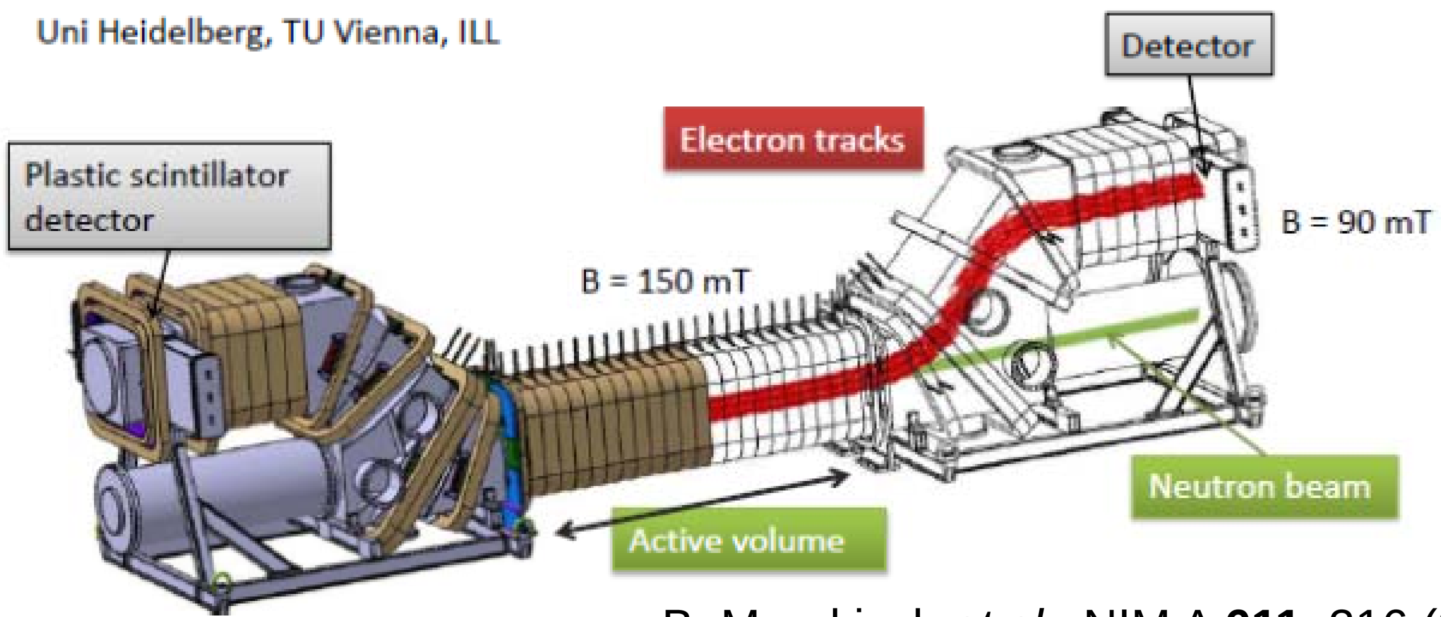
ν-Asymmetrie $\quad C = -\,0.239 \pm 0.003$, PRL **100**, 151801 (2008)





Perkeo III is state of art of CN beta decay

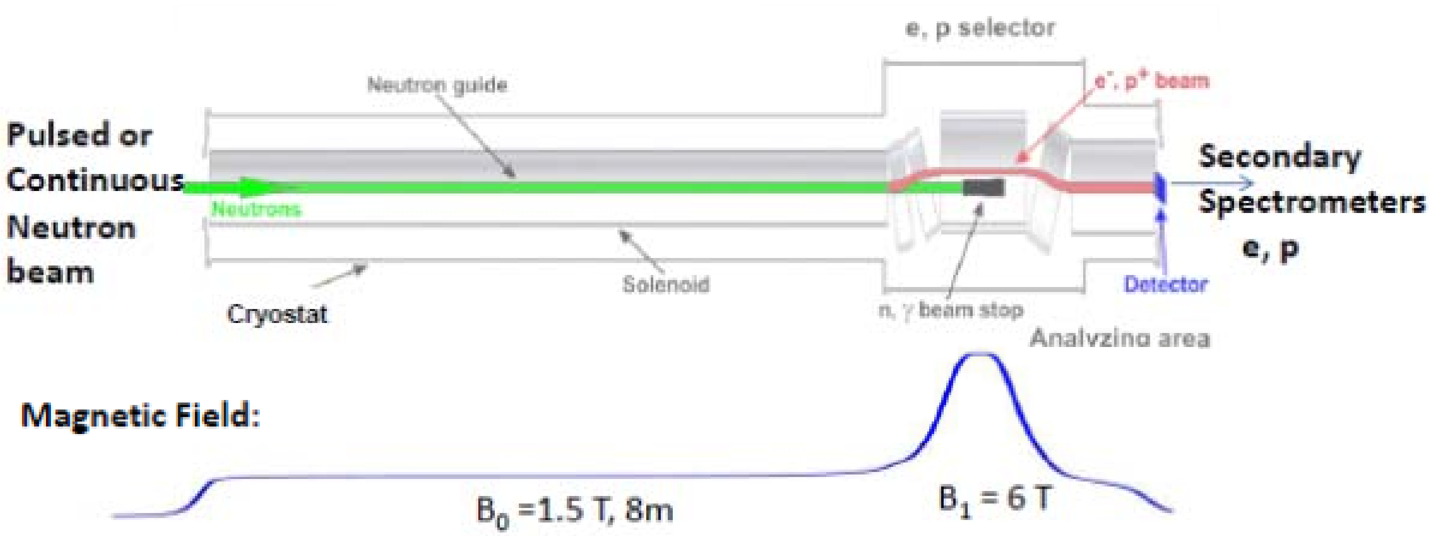
- Backgrounds eliminated using pulsed beam
- 50 kHz decay rate
- Total uncertainty expected to be $\Delta A/A$=2.1e-3
- Results very soon!



B. Maerkisch *et al*., NIM A **611**, 216 (2009)

PERC is the next generation

- **P**roton **E**lectron **R**adiation **C**hannel
- 8 m flight path maximizes statistics
- 6 T field pinch minimizes backscatter, field inhomogeneity effects
- To be installed in flight path at FRM-2
- All systematics expected to be $O(10^{-4})$



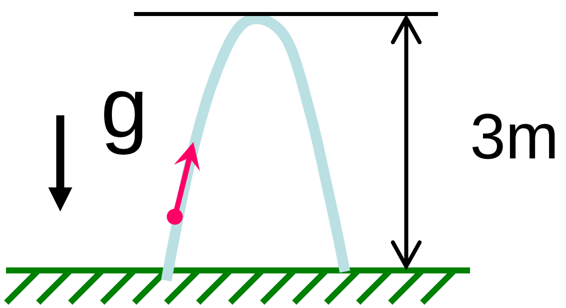
D. Dubbers *et al*., NIM A **596**, 238 (2008)

Interlude — What are ultracold neutrons?

- Very slow neutrons ($v < 8$m/s)
- Totally reflected by some materials

- Hence, they can be totally confined within a bottle for periods in excess of 100 seconds.

- Typically: velocity < 8m/s
  kinetic energy < 3×10^{-7} eV
  wavelength > 500Å
  or temperature < 4 mK

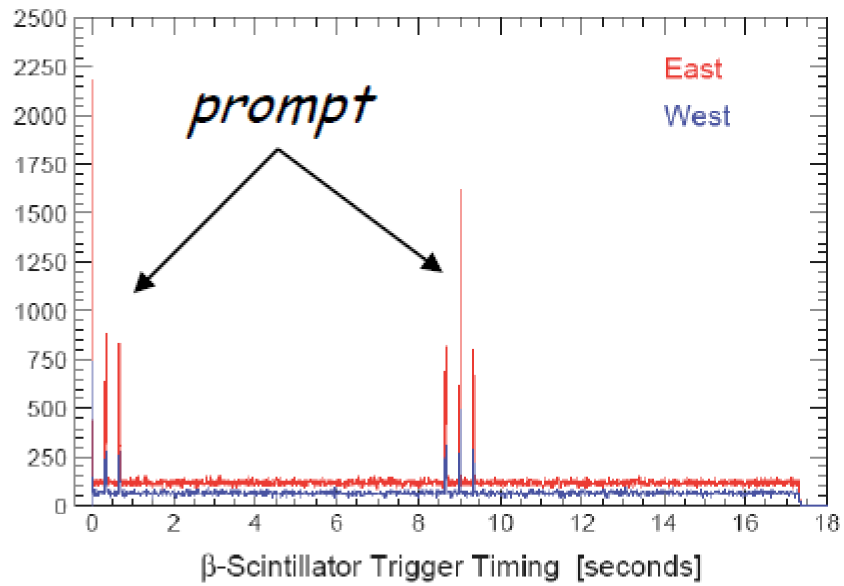


- *cf:* Gravity: 10^{-7} eV/ meter.
  Magnetic field (μB): 10^{-7} eV/ 1.7 T.

UCNA Experiment — General Approach

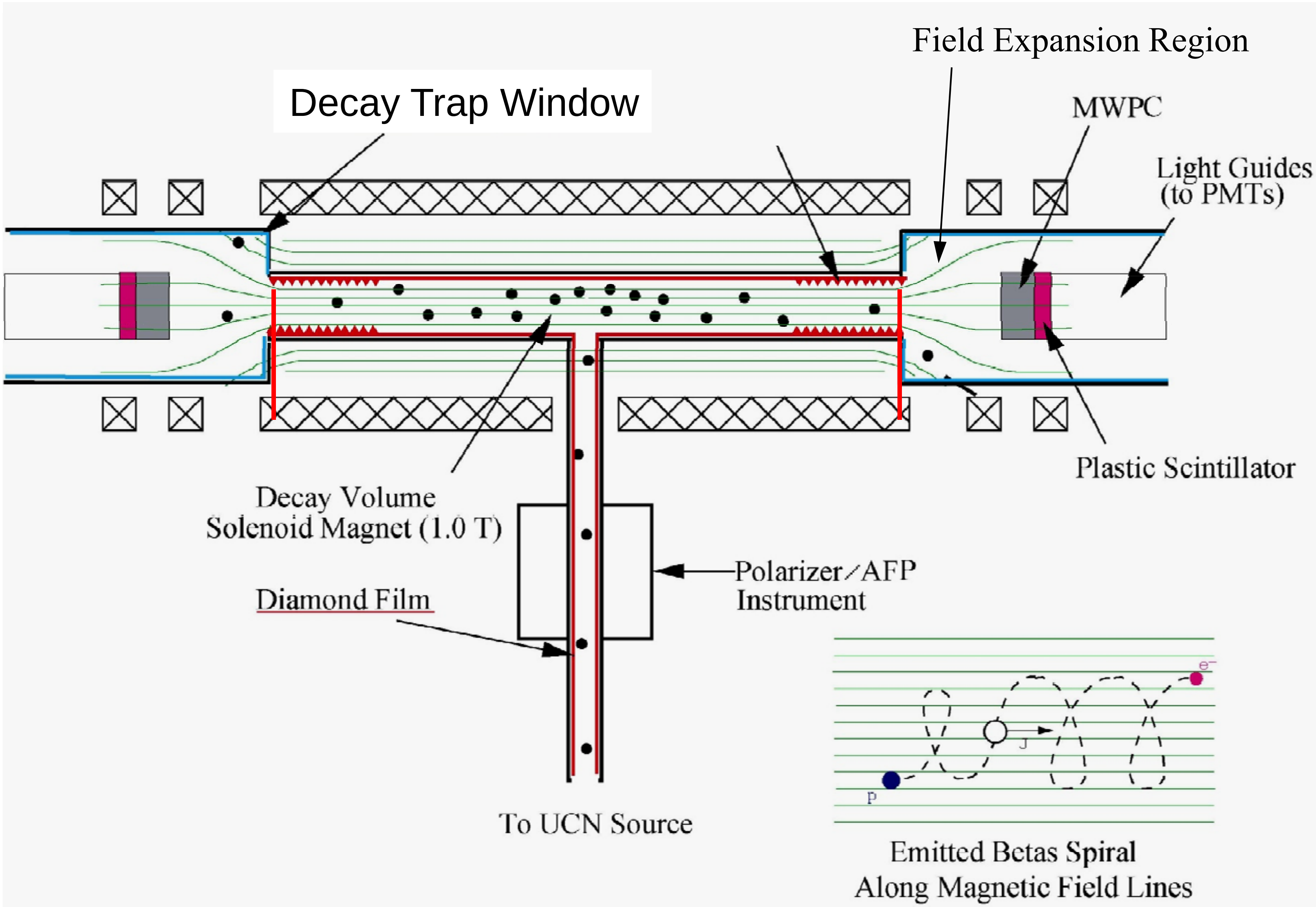
Novel features: UCN from pulsed spallation source
MWPC + plastic scintillator as β detector
Ultimate Goal: 0.2% measurement of *A* ($\delta A/A$ = 0.2%)

- Neutron Polarization
  - UCN (can produce >99% polarization with 7T magnetic field)
  - Copper and diamond-like carbon coated neutron guide (low depolarization)
- Background
  - Pulsed UCN source
  - MWPC+Plastic scintillator
- Electron backscattering
  - MWPC+Plastic scintillator
- Fiducial volume selection
  - MWPC



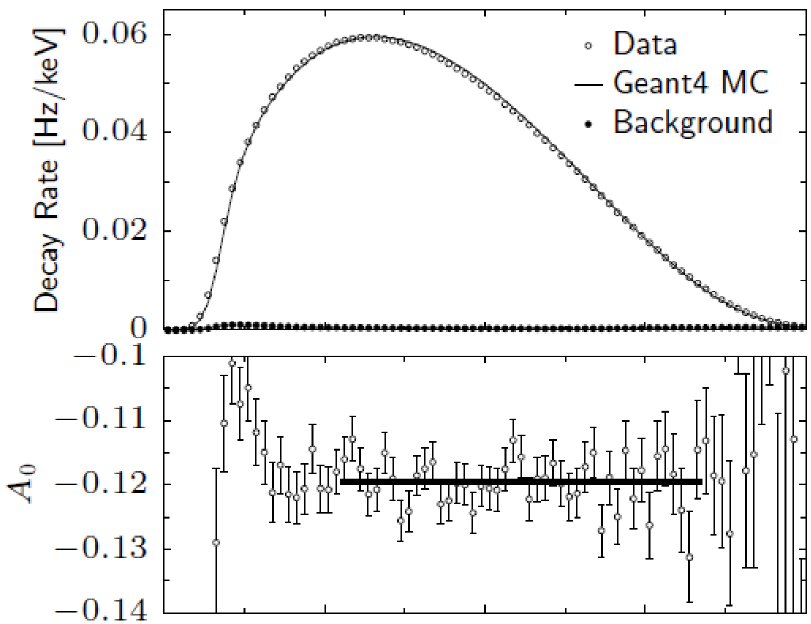
Plaster *et al.*, PR C **86**, 055501 (2012)

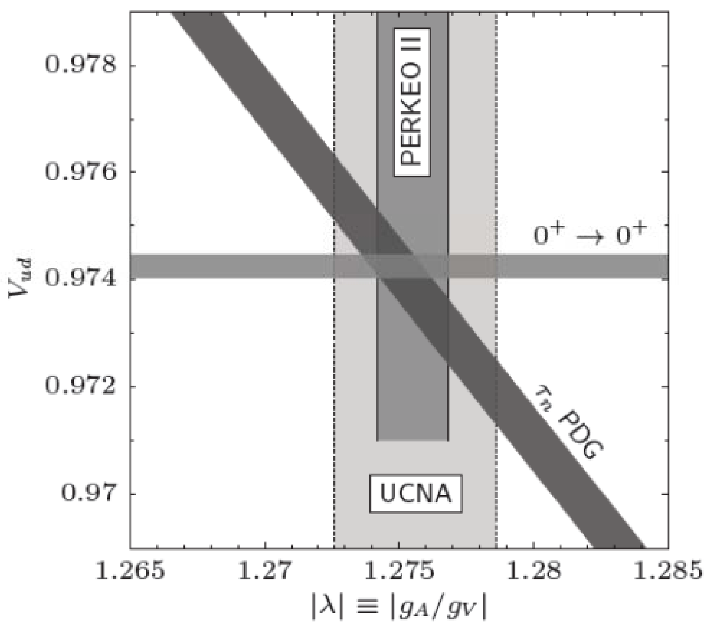
UCNA Experiment — Apparatus



UCNA Status

- Taking production data since 2009 using LANL UCN source
- Latest result: A=-0.11954(112)

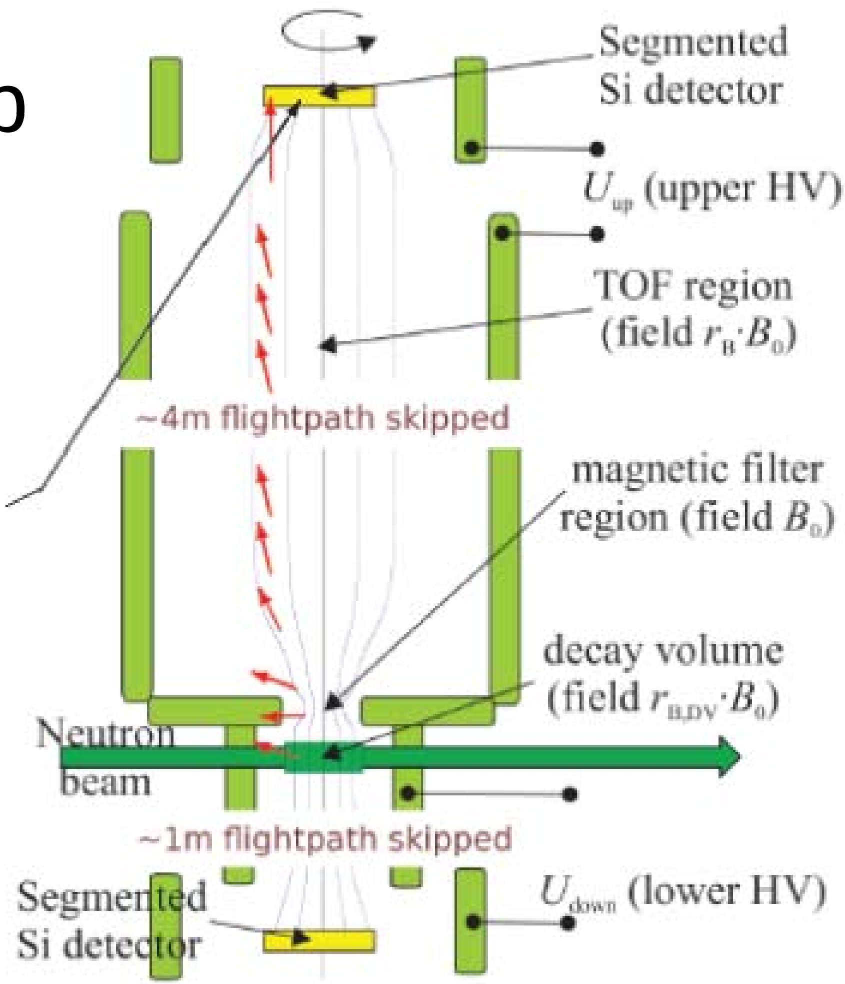




Mendenhall *et al*., arXiv 1210.7048 (2012)

Nab experiment in design stage

- Nab will measure a,b at SNS in US
  - Recall a=electron-neutrino correlation
  - Reconstruct opening angle from E_p, E_e
  - E_e from Si detectors, E_p from TOF



Neutron Lifetime affects BBN

Light elements from ^{2}H up to ^{7}Li created in "first three minutes"

Weak reactions between particles:

$$n + e^{+} \leftrightarrow p + \bar{\nu}_e, \qquad \sigma_\nu \sim 1/\tau_n$$

$$n + \nu_e \leftrightarrow p + e^{-}, \qquad \text{(all have same Feynman diagram)}$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e. \qquad \tau_n$$

At time $\approx$ 1 s, at "freeze-out" temperature $T_f \approx 1$ MeV:

neutron to proton ratio frozen to:

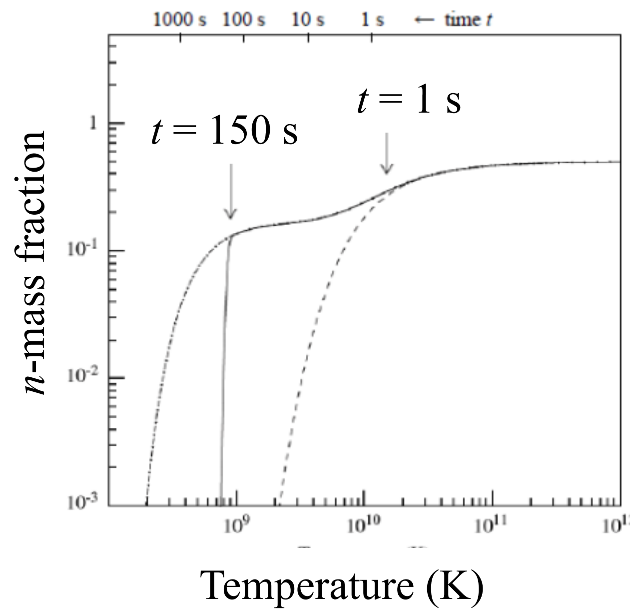
$$n/p = \exp(-\Delta m/kT_f) \approx 1/6.$$

$$\Delta m = m_n - m_p = 1.3 \text{ MeV}$$

After another $\approx$ 150 s, practically all neutron wind up in ^{4}He,

i.e., He mass fraction $Y_p = 2 \times$ neutron mass fraction $\approx 25\%$.

Primordial nucleosynthesis:



Dubbers 2013

And ratio of He/n depends directly on n lifetime: 1% lifetime uncertainty shifts calculated He fraction of Y=0.2480+/- .0003 by 0.0015, or 5 sigma!

Lifetime uncertainty has grown recently

And central value has shifted by almost 1%!

$$\begin{array}{ll} \text{PDG 2001-2010} & \tau_n = (885.7 \pm 0.8)\ \text{s}\ (S=1) \\ \text{Serebrov } et\ al.\ 2005 & \tau_n = (878.5 \pm 0.8)\ \text{s} \\ \text{Pichlmaier } et\ al.\ 2010 & \tau_n = (880.7 \pm 1.8)\ \text{s} \\ \text{PDG 2012} & \tau_n = (880.1 \pm 1.1)\ \text{s}\ \ (S=1.8) \end{array}$$

Serebrov *et al.*,
PL B **605**, 72 (2005)

Pichlmaier *et al.*,
PL B **693**, 221 (2010)

Beam Method: Count the dying

PHYSICAL REVIEW C **71**, 055502 (2005)

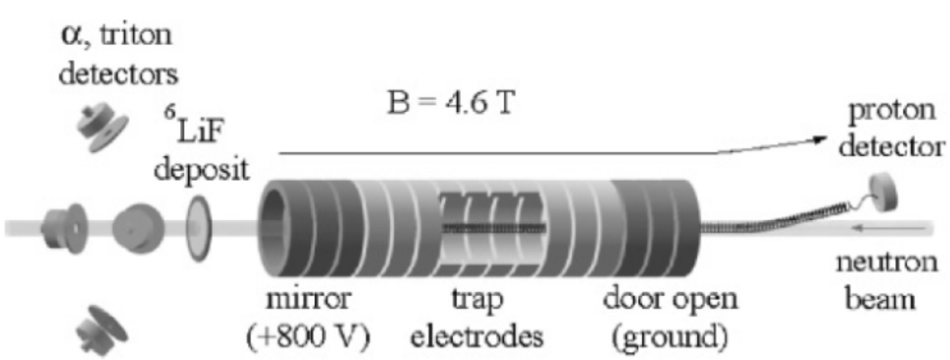
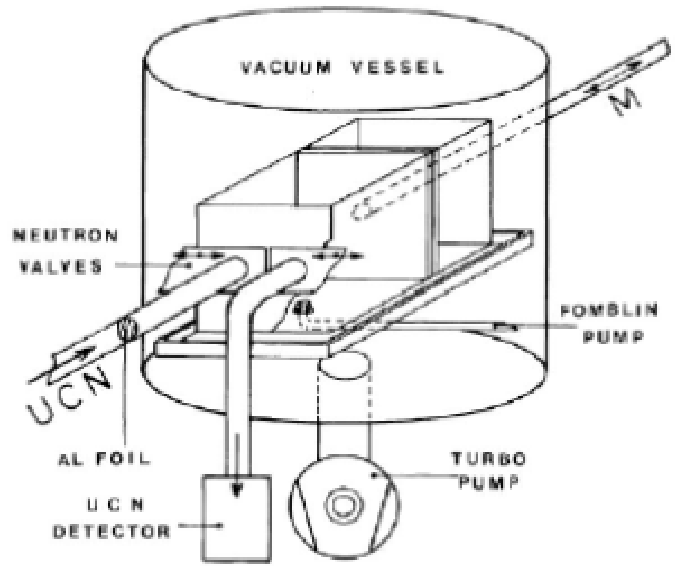


FIG. 2. Experimental method for measuring lifetime by counting neutrons and trapped protons.

Danger: absolute monitor efficiency needed!

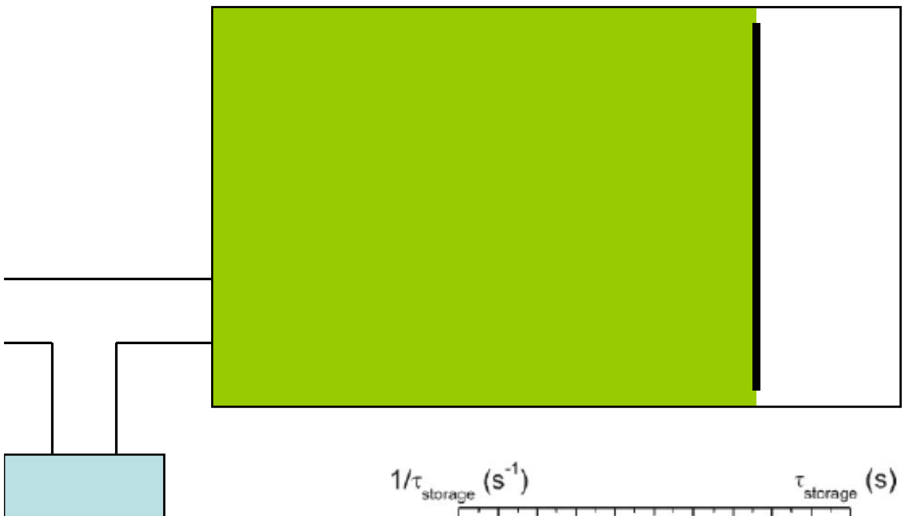
Bottle method: count the survivors

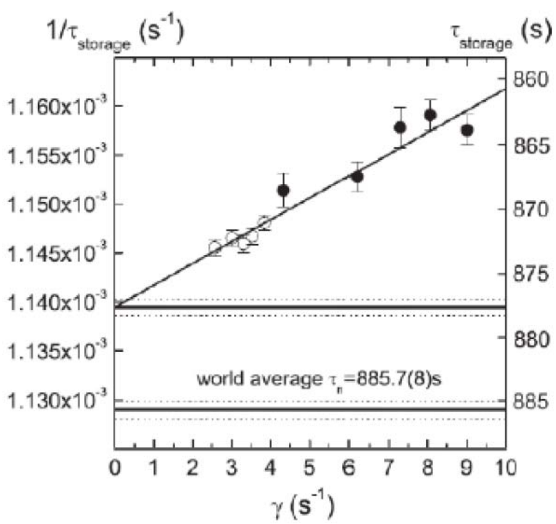


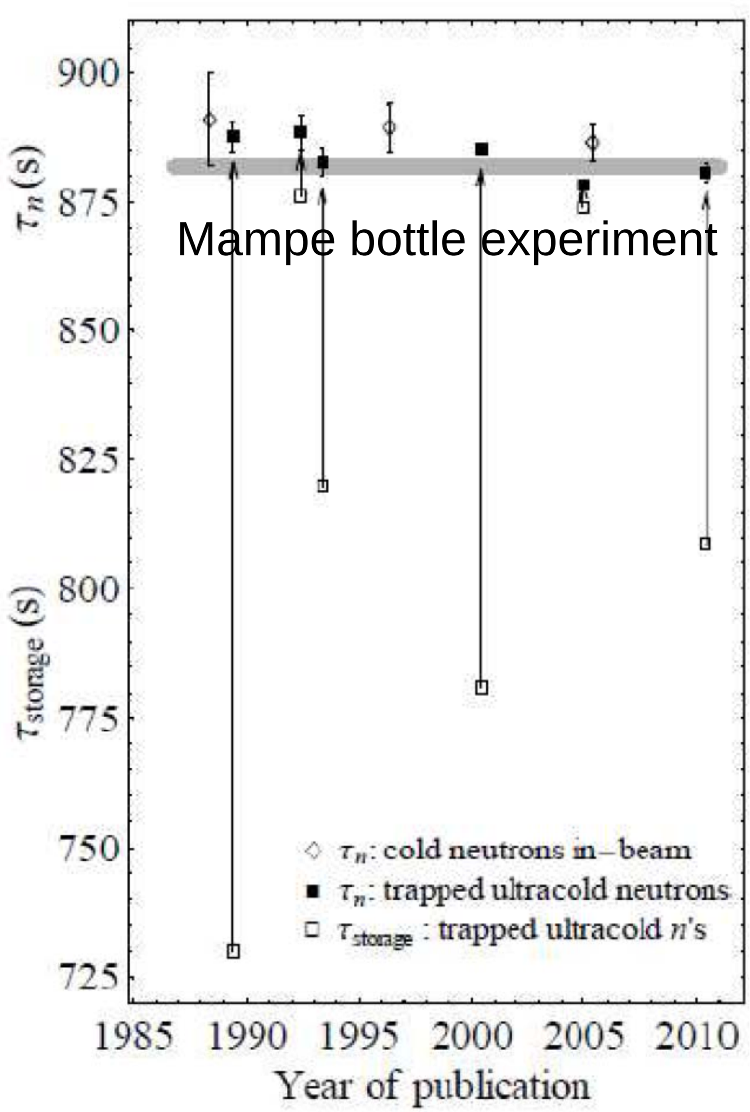
$$1/\tau_{\text{storage}} = 1/\tau_n + 1/\tau_{\text{loss}}$$

Wietfeldt and Greene,
Rev. Mod. Phys. **83**, 1173 (2011)

Material bottle experiments involved 100 s extrapolations due to wall losses



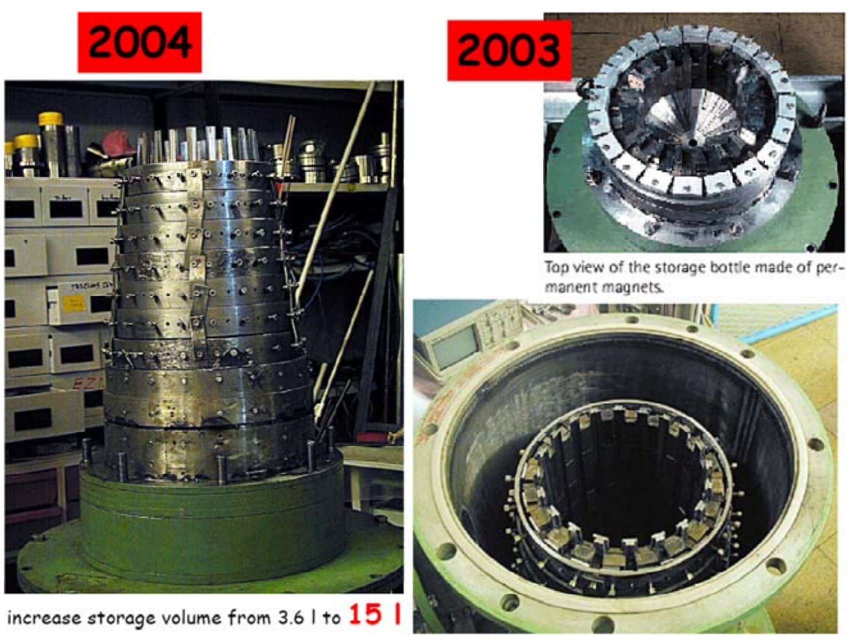




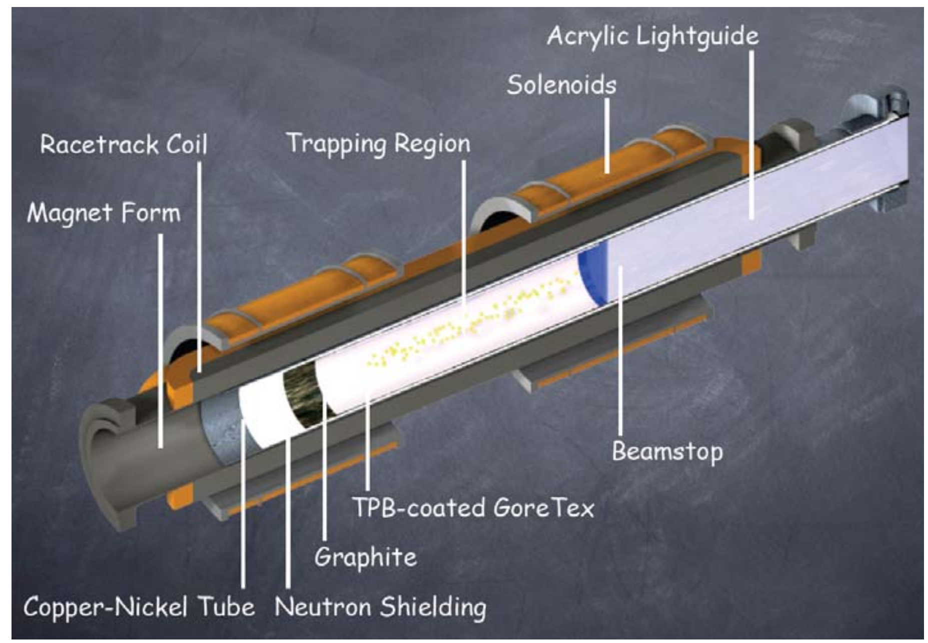
Solution: eliminate wall losses using magnetic bottle

- A new crop of experiments using magnetic traps is now under development
- Stern-Gerlach effect repels polarized neutrons from walls

ILL Ezhov Bottle filled with vacuum



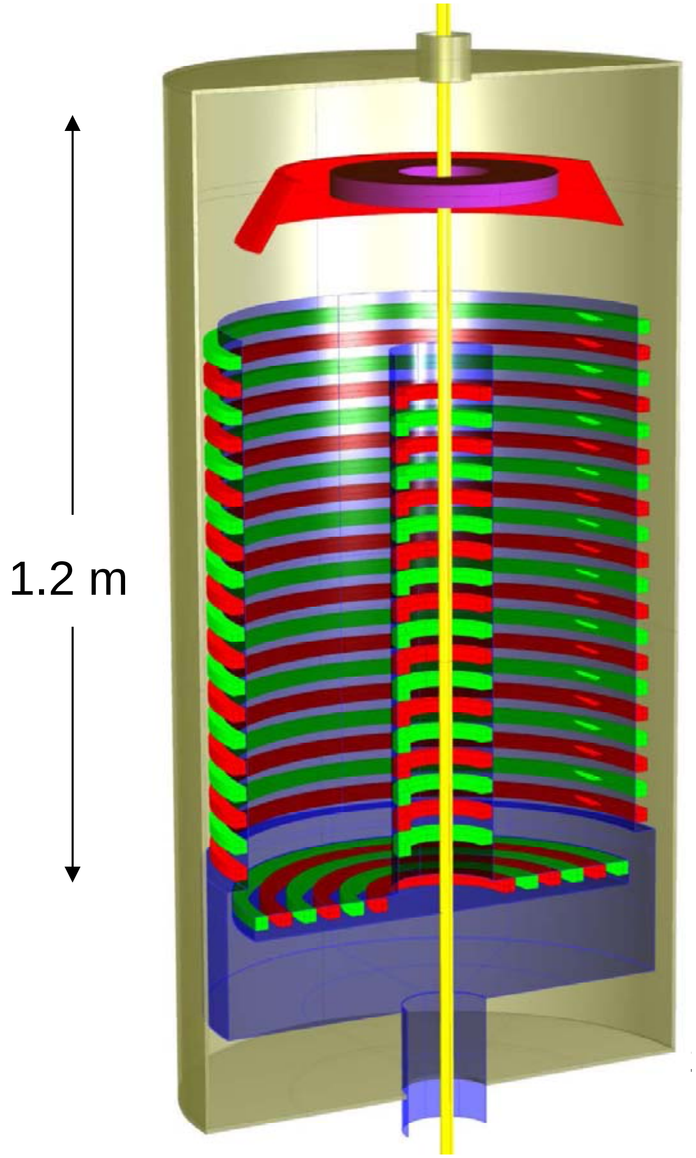
NIST UCN trap filled with superfluid 4He



Both have acquired commissioning data;
HOPE at Munich also in design stage

Penelope experiment under development

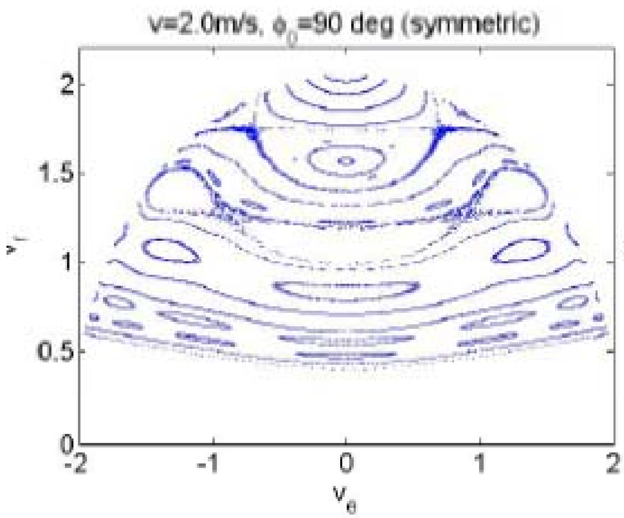
- Superconducting multipole
  – Field zero in center eliminated by inner conductors
- Filled with UCN from FRM-2 through gap in bottom
- Decay products detected at top, guided by field lines
- Spectrum cleaned using absorber lowered from top
- Magnet now under construction



An outstanding problem: phase space evolution

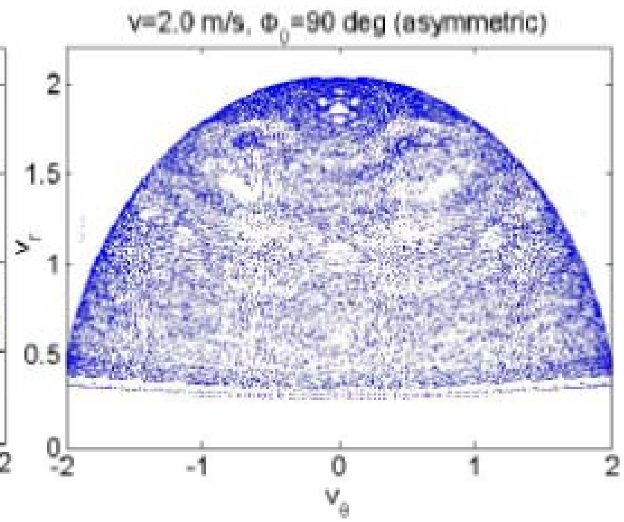
- Neutron losses on scale of neutron lifetime (quasibound orbits)
- Detector efficiency changes with time
- Must fill phase space evenly, quickly: chaos!

Symmetric Trap has stable orbits



Thin stochastic regions bounded by KAM curves.

Asymmetric Trap has chaotic orbits



Strong perturbation, KAM curves are destroyed.

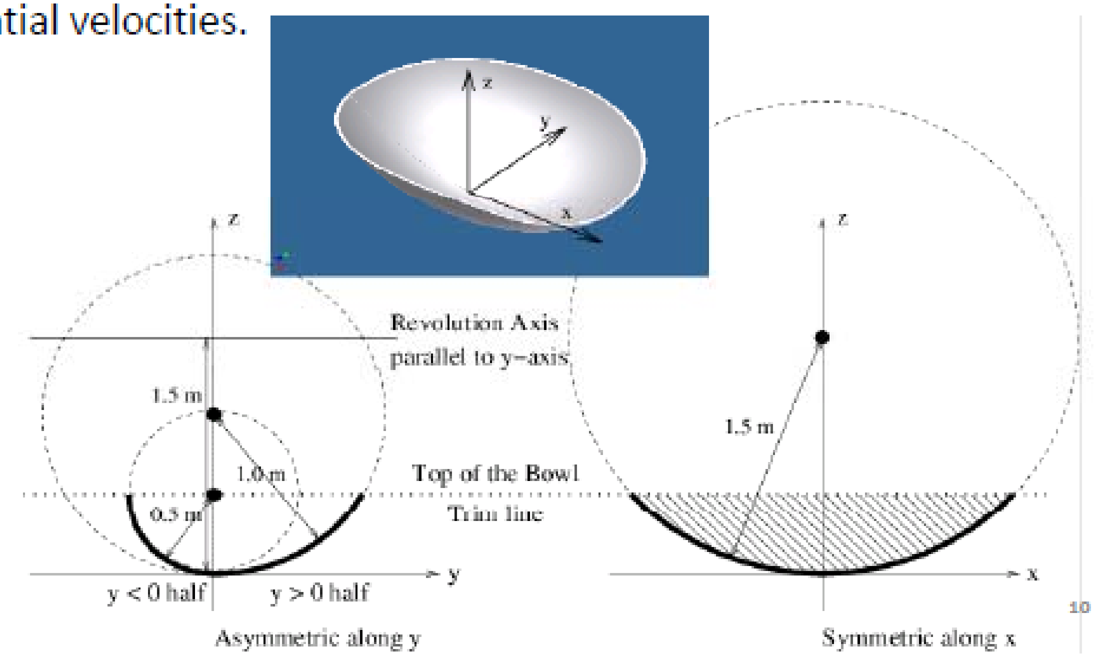
C.-Y. Liu, 2012

UCNTau experiment designed to overcome phase space issues

Asymmetric Trap → Phase Space Mixing

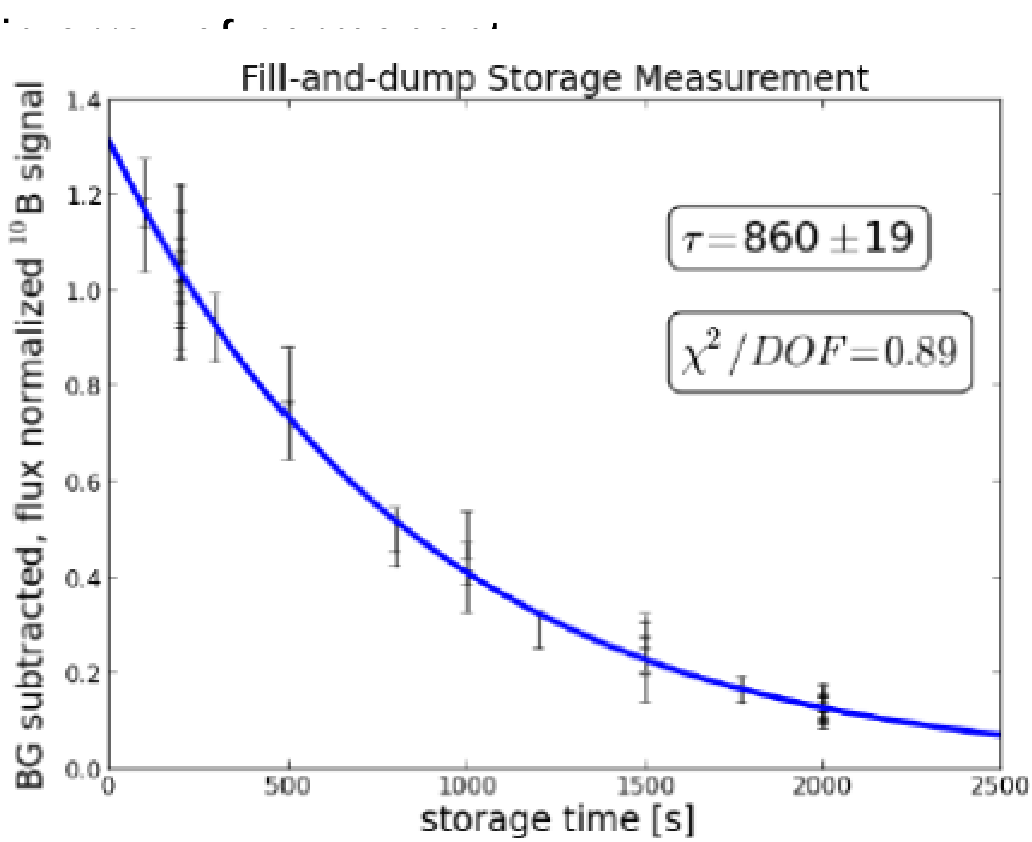
- **Low symmetry** (together with **field ripples**) induces states mixing between circular orbits, through chaotic motion (or not).

- → **quick cleaning** (~ seconds) of the quasi-bound UCN with large tangential velocities.

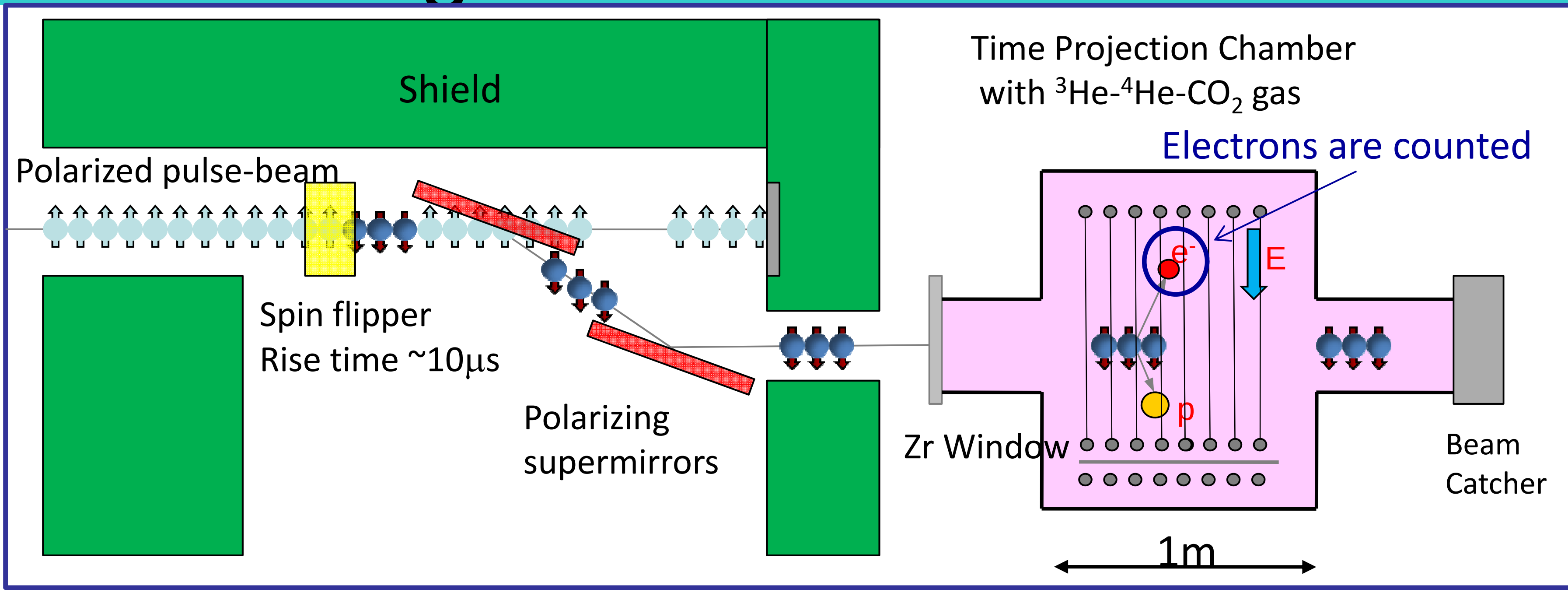


UCNTau Experiment now commissioning

- Asymme
  magnets
- Holding
  polarizat
- UCNs fr
  filled thr
- Neutrons
  absorpti
  inserted
  activatio
- Has stor
  first time



New beam-type experiment also nearing first results at J-Parc



- TPC detects electrons from n decay and protons from n-absorption on 3He simultaneously
- Leading systematic uncertainty expected to be pressure of 3He
- Physics run planned for 2013

Takahito Yamada, U. Tokyo, 2012

Conclusions

- Precision neutron beta decay measurements can search for physics beyond the standard model with a reach competitive with HEP
- And also underlie wide areas of nuclear and particle physics
- Beta decay correlation experiments in progress and next generation in development: overconstrained SM parameters allow search for BSM effects
- Neutron lifetime problem needs experimental resolution: it is coming, with new experiments worldwide approaching production data
- Review papers:
  - Dubbers and Schmidt, Rev. Mod. Phys. **83**, 1111 (2011)
  - Abele, Pro. Part. Nucl. Phys. **60**, 1 (2008)
  - Wietfeldt and Greene, Rev. Mod. Phys. **83**, 1173 (2011)
- Thank you to my collaborators and especially Dirk Dubbers, Bastian Maerkisch, Hartmut Abele, Chen-Yu Liu, Albert Young